

**DETECTING THE LIQUID CORE IN CONTINUOUS CASTING SLABS BY  
LOAD TORQUE ESTIMATION IN UNBENDING ZONE \***

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**Abstract:** The development in continuous casting process has been strongly dominated by the demands of quality improvement and reduced costs for steel products in recent years. To achieve these goals consideration has been given by increasing the velocity of casting process. In that case a portion of a cross section of the slab are still licked in the unbending zone. Information about the deformation, stress and strain in solid shells is quit important in terms of the cost quality. These information are obtained by load torque estimation using the electrical quantities of the drive system for the unbending zone. A sensor less drive system with induction motor is considerate. The electrical drive systems are controlled in torque and speed. The measurements of voltage and current components and the imposed speed are the inputs for the real time load torque estimator. The estimated load torque is compared with the calculated maximal load torque for the entirely solidified slab state. From this comparison results the thickens of the slab licked zone.

**Keywords:** estimated load torque, electrical drive systems.

**1. INTRODUCTION**

The continuous casting process has been adopted word-wide by steel industries over the last 2 decades owing to its inherent advantage of low cost, high yield and ability to achieve a high quality cast product. Direct casting techniques enable the production of steel slabs directly from molten steel.

These technology aims on shortening the processing chain between steel production and rolling the material to desired dimensions. In the last decade methods for casting thin steel strips are developed and tested.

In the continuous casting process there are two distinct zones: bending zone and unbending zone. If the casting process velocity is slow, the unbending process is developed with completely solidified slab (Fig.1.a).

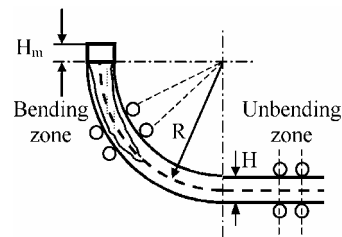


Fig.1a Process with small solidification length  $l_s$

When the casting velocity increases the slab is not totally solidified at the unbending zone (Fig.1.b).

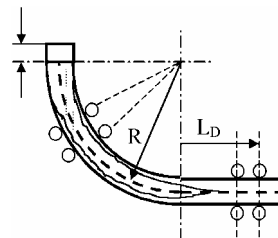


Fig.1b Process with large solidification length  $l_s$

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We consider the specific plastic deformation energy as

$$(1) w_{sp} = \sigma_p(T, \chi) \cdot \varepsilon$$

where the stress  $\sigma$  is a function of slab temperature  $T$  and quality variable  $\chi$  and  $\varepsilon$  is the plastic strain.

The corresponding deformation torque is

$$(2) M = \frac{\Delta W}{\Delta t} \cdot \frac{1}{\Omega} = \sigma \cdot \varepsilon \cdot H(x) \cdot \frac{v}{\Omega} \cdot L$$

where  $v$  is the casting velocity,  $\Omega$  is drive roles speed,  $L$  the slab width, and  $H(x)$  the thickness of the solid slab portion.

From (2) we obtain the traction force

$$(3) F_t = 2 \cdot \sigma_p \cdot \varepsilon \cdot H(x) \cdot L$$

The model of metallurgical process is illustrated in fig. 2, where we denote by  $l_s$  the solidification length. The optimal solidification length is

$$(4) L_M = H_m + \frac{\pi \cdot R}{2} + L_D$$

In fig.2 we denote by  $K$  the main parameter of the solidification process. This parameter must be adjustable and is determined mainly by cooling flow water  $Q$ .

## 2. PROBLEM FORMULATION

The continuous casting process has strong non-linearity. The control of the process requires a priori information of the slab solidification state. The load torque of the electrical drive system for the unbending zone characterizes the state of solidification process. Estimating the load torque of the electrical drive system we can calculate, by mean of the solidification process model, the solidification state, if we know the solidification parameter  $K$ . The parameter  $K$  is uncertain and direct way of solidification state determination is not valid.

The following adaptive model of the solidification process is proposed (fig.3). The estimated load

torque  $\hat{m}_r$  is compared with the load torque obtained from the solidification model. The error is the base for the solidification parameter  $K$  adjustment.

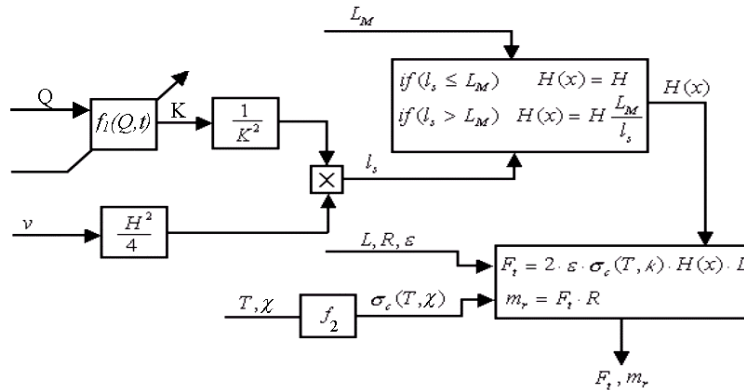


Fig.2 The model of solidification process

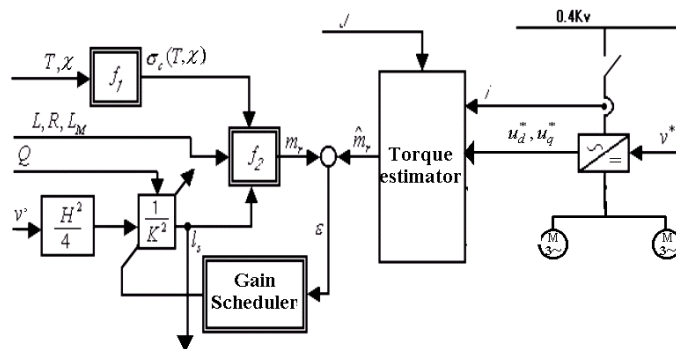


Fig.3 The adaptive model of the solidification process based on the load torque estimator

### 3. THE LOAD TORQUE ESTIMATOR

The load torque estimator realizes the inversion of the drive system movement equation. Generally speaking, the model of the estimator is represented in fig. 4, where we utilise a controller which try to maintain the estimation error  $\varepsilon_{es}$  near zero.

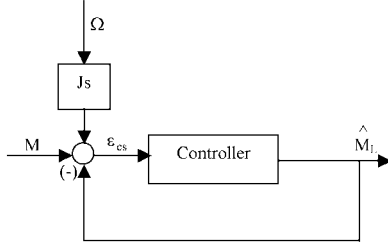


Fig.4 The inversion of the system movement equation and the controller associated

In fig. 4,  $M$  represents the motor electromagnetic torque,  $M_L$  is the load torque and  $J$  is the total moment of inertia. The controller design was carried out with the MATLAB control system toolbox. The loop were closed using pole placement and frequency domain methods. The estimator time response must be faster as possible. The best results was obtained with Bode-diagram in accordance with "symmetrical optimum criteria"

The estimator`s discret equations used in the paper was :

$$(5) u_{es}(k+1) = u_{es}(k) + (m(k) - m_{es}(k))t / J$$

$$(6) \hat{m}_L(k+1) = c_{es} \hat{m}_L(k) + J \omega_{cr} (1 - c_{es}) \frac{(u_{es}(k+1) - om(k))}{t}$$

where  $t$  is the sampling period,  $\omega_{cr}$  is the space loop cross-over frequency and

$$c_{es} = \exp(-t / t_{sig})$$

where  $t_{sig}$  is the filter time constant.

### 4. AC DRIVE CONTROL SYSTEM WITH DYNAMIC MODEL AND LOAD TORQUE COMPENSATOR

The actual industrial power converters for induction machine AC drives are made in various configuration beginning with a simple low cost U / Hz open loop solution and up to the field orientation technique where the most sophisticated system is the sensor less direct torque control.

In the following we consider a low cost open loop speed controlled system with the feed-forward reference trajectories generation (fig.5)

In order to built the proposed system the following problems have to be solved:

- The machine torque  $\hat{m}$  evaluation on the base of the measurable power converter currents and voltage quantities;
- The torque and flux controllers implementation which produce the  $u_{ds}^*$  and  $u_{qs}^*$  voltage components controls;
- Calculating the open loop  $\omega_1^*$  reference control for supply voltage pulsation;
- The control law for torque reference  $m^*$  and speed reference  $\omega^*$  generation;
- The load torque estimation based on the estimated machine torque  $\hat{m}$  and reference speed  $\omega_1^*$ ;

The well-known machine equations in the field-oriented coordinates are:

$$(12) T_2 \frac{di_{m2}}{dt} + i_{m2} = i_{d1}$$

$$(13) \omega_1 = \omega + \frac{R_2 \cdot i_{q1}}{L_{12} \cdot i_{m2}}$$

$$(14) m = \frac{3}{2} \cdot p \cdot \frac{L_{12} \cdot i_{m2} \cdot i_{q1}}{1 + \sigma_2}$$

where  $T_2$  is the rotor time constant;  $i_{d1}$  and  $i_{q1}$  the stator currents components;  $i_{m2}$  is magnetizing current for the rotor flux  $\varphi_2 = L_{12} \cdot i_{m2}$ ;  $\omega_1$  is angular frequency for supply voltage;  $\omega$  is the motor angular velocity;

From the torque equation (14) we have:

$$(15) i_{q1} = \frac{2 \cdot m \cdot (1 + \sigma_2)}{3 \cdot p \cdot L_{12} \cdot i_{m2}}$$

The angular frequency  $\omega_1$  results from (13) and (15):

$$(16) \omega_1 = \omega + \frac{2 \cdot R_2 \cdot m \cdot (1 + \sigma_2)}{3 \cdot p \cdot (L_{12} \cdot i_{m2})^2}$$

In fig.5 the angular frequency  $\omega_1$  was calculated with the following relation derived from (16):

$$(17) \omega_1^* = \omega^* + K_{m1} \cdot (m^* + \Delta m)$$

where  $\Delta m$  is the torque controller error

$$\Delta m = m^* - \hat{m}$$

and

$$(18) K_{m1} = \frac{2 \cdot R_2 \cdot (1 + \sigma_2)}{3 \cdot p \cdot (L_{12} \cdot i_{m2})^2}$$

The machine torque estimator are usually built with the field orientation model (14), but this relation was already used for the slip velocity estimation in (17) and (18):

$$(19) \omega_{slip} = \frac{2 \cdot R_2 \cdot m \cdot (1 + \sigma_2)}{3 \cdot p \cdot (L_{12} \cdot i_{m2})^2}$$

Our solution is based on stator currents measurements using the machine stator equation:

$$(20) \underline{u}_1 = R_1 \cdot \underline{i}_1 + j\omega_1 \underline{\varphi}_1 + \frac{d\underline{\varphi}_1}{dt}$$

Multiplying these equation by  $\underline{i}_1^*$  where \* denotes the complex conjugate and taking the reels parts, we have:

$$Re(\underline{u}_1 \underline{i}_1^*) = R_1 \cdot i_1^2 + Re j \omega_1 \underline{\varphi}_1 \underline{i}_1^* + Re \frac{d\underline{\varphi}_1}{dt} \underline{i}_1^* \quad (21)$$

From the above equation we obtain the electromagnetic torque:

$$(22) m = \frac{p}{\omega_1} = Re \cdot j \underline{\varphi}_1 \underline{i}_1^*$$

where  $\underline{\varphi}_1$  is the stator flux

$$(23) \underline{\varphi}_1 = \varphi_{d1} + j \cdot \varphi_{q1}$$

From (22) and (23) results

$$(24) m = \varphi_{d1} \cdot i_{q1} - \varphi_{q1} \cdot i_{d1}$$

Taking in account the three phases of the electric machine and  $p \neq 1$ , we have

$$(25) \hat{m} = \frac{2}{3} p \cdot (\varphi_{d1} \cdot i_{q1} - \varphi_{q1} \cdot i_{d1})$$

The flux components  $\varphi_{d1}$ ,  $\varphi_{q1}$  results by integrating the machine stator equation (20).

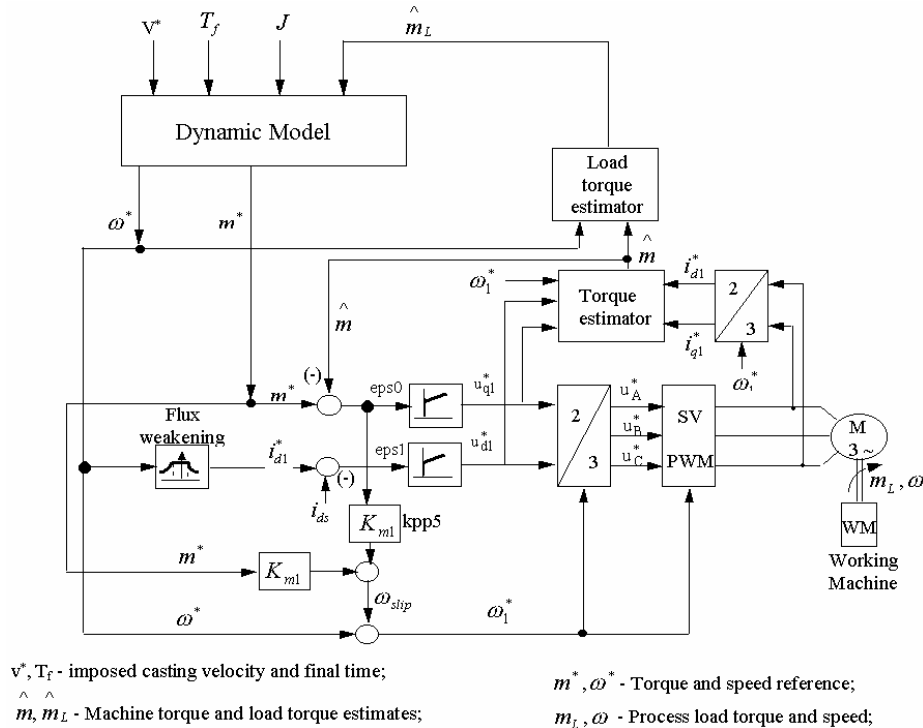


Fig.5 Sensor less open loop speed and position tracking szstem for induction machine motion control

First, we have from (20)

$$(26a) \quad u_{d1} = R_1 \cdot i_{d1} - \omega_1 \cdot \varphi_{q1} + \frac{d\varphi_{d1}}{dt}$$

$$(26b) \quad u_{q1} = R_1 \cdot i_{q1} + \omega_1 \cdot \varphi_{d1} + \frac{d\varphi_{q1}}{dt}$$

The difference equations corresponding to equations (26) and (27) are

$$(27a) \quad \varphi_{d1}(k+1) = \varphi_{d1}(k) + t_s \cdot (u_{ds} - R_1 \cdot i_{d1}(k) + \omega_1 \cdot \varphi_{q1}(k))$$

$$(27b) \quad \varphi_{q1}(k+1) = \varphi_{q1}(k) + t_s \cdot (u_{qs} - R_1 \cdot i_{q1}(k) - \omega_1 \cdot \varphi_{d1}(k))$$

$$(28) \quad \hat{m} = \frac{2}{3} p \cdot (\varphi_{d1}(k+1) \cdot i_{q1}(k) - \varphi_{q1}(k+1) \cdot i_{d1}(k))$$

with  $t_s$  as sampling period.

In fig.5 we have two controllers. The torque controller takes the reference  $m^*$  from the motion model and the feedback  $\hat{m}$  from torque estimator. The references  $i_{d1}^*$  for de flux controller take in account the possibility of the flux weakening for large speed over the rated values.

The best dynamic behavior are obtained with adaptive PIDFF (proportional, integral, derivative, feed-forward) controllers or with new neuro-fuzzy controls technique. The linear torque and flux controllers do not produces the same responses for different references levels due to non linearity of induction machine. For this reason a gain scheduling algorithm was utilized.

## 5. EXPERIMENTAL RESULTS

The process control objective is to keep the solidification length as close as possible to  $L_M$  value (4). The solidification length is a no measurable quantity. For this reason a mathematical model for solidification process was built. But the process parameters are not well known. Using the electrical drive load torque estimation we get the information about the deformation, stress and strain in solid slab shells and then the corrections of the solidification model parameters are possible.

In the following, different testing results will be presented. In that aim the casting velocity  $v$  and cooling water flow  $Q$  was modified, resulting a load torque variation for electrical drive system. The load torque estimator follows quite well the dynamic of the real process load torque. The test was effectuated under following conditions: after the initialization of casting process the velocity "vitant" and the flow "debita" was obtained and then the perturbations "vitimp" and "debiti" was applied.

Figure 6, 7 shows the variations of the length solidification and load torque when the casting velocity increases or decreases and cooling water flow is constant

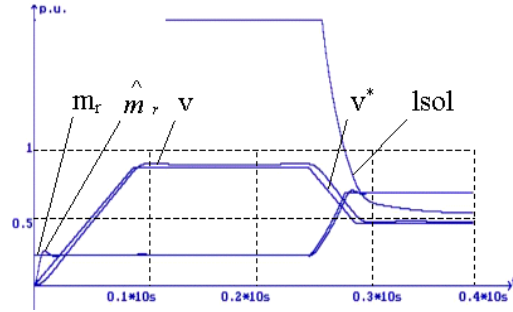


Fig. 6: vitan = 0.8m/min; vitimp = 0.5m/min  
Debita = 80% ; debiti = 100%

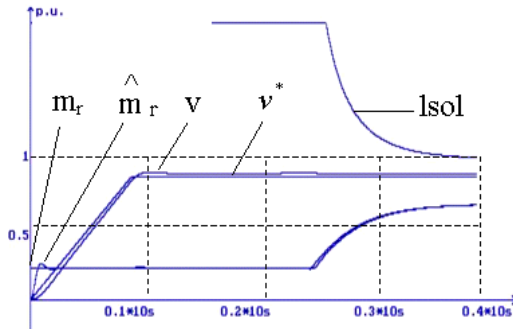


Fig. 7: vitan=0.8m/min; vitimp=0.5m/min;  
debita=80%; debiti=100%

Figure 3,4 shows the same variations when the cooling water flows increase or decrease when costing velocity is constant.

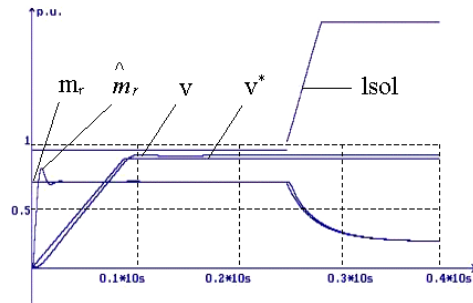


Fig. 8: vitan = 0.8m/min; vitimp = 0.8m/min ;  
debita = 100% ; debiti = 80%

The technology aim is to maintain a constant solidification length. For these reason the variations of the casting velocity is correlated with the cooling water flow.

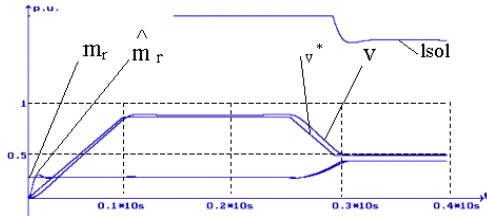


Fig. 9:  $v_{itan} = 0.8\text{m/min}$ ;  $v_{itimp} = 0.5\text{m/min}$  ;  
 $debita = 80\%$  ;  $debiti = 80\%$

In figure 10,11 are represented the test results for simultaneous variations of the velocity and cooling water flow.

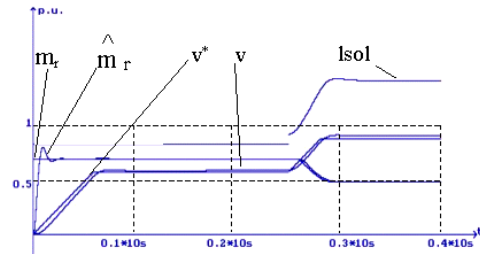


Fig.10:  $v_{itan} = 0.5\text{m/min}$ ;  $v_{itimp} = 0.8\text{m/min}$  ;  
 $debita = 93\%$  ;  $debiti = 93\%$

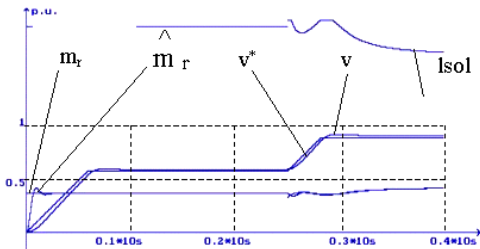


Fig.11:  $v_{itan} = 0.5\text{m/min}$ ;  $v_{itimp} = 0.8\text{m/min}$  ;  
 $debita = 80\%$  ;  $debiti = 90\%$

In figure 10 the variations of the velocity and cooling water flow are well correlated because the solidification length ( $l_s$ ) are quite constant.

## 6. CONCLUSIONS

A load torque estimator to detect the solidification length in continuous casting steel process is proposed in this paper. In the case of an AC drive system the load torque estimator was build whit an electromagnetic machine torque estimator based on the voltage components controls and current measurement. The same load torque estimator was successfully used for feed-forward load disturbance compensation to increase the performance of drive control system.

## 7. REFERENCES

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